Calculation of the Excitation and Ionization State of Plasma for the Electron κ–distributions

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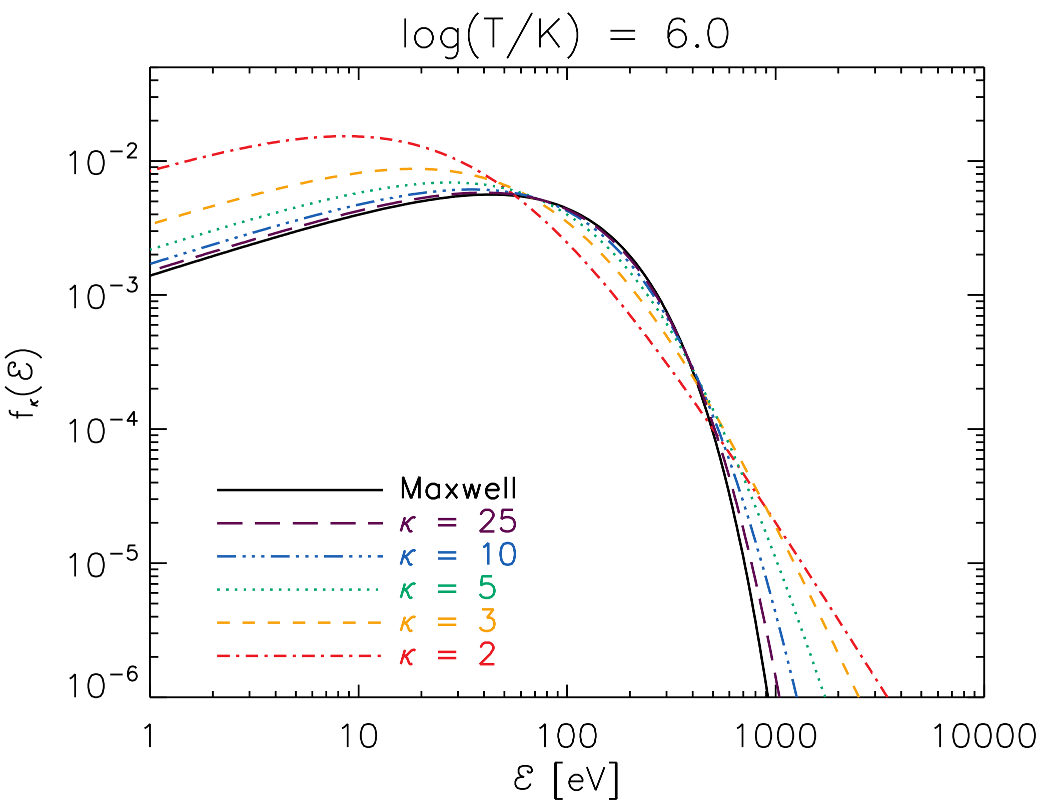
Motivation

- for the interpretation of the observed emission – we need to know the microphysics
- theoretical derivation of the κ-distribution in the stellar/solar corona (e.g. Scudder, 1979; Scudder & Karimabadi, 2013; Meyer-Vernet, 2007; Livadiotis & McComas, 2009, 2013...)
- Maksimovic et al. (1997): solar wind velocity distribution is well approximated by a k-distribution
- coronal source of the flare X-ray emission can be described by a κ-distribution: e.g. Kasparova & Karlicky, 2009, Oka et al., 2013; theoretical model: Bian & Stackhouse, 2014 (see also RHESSI nuggets)
- Dzifčáková & Kulinová (2011): relative intensities of Si III in the solar transition region correspond to the κ-distribution
- distribution with an enhanced high energy tail can be formed in corona due to heating (e.g. by micro flares, waves, ...)
- shape of the distribution affects the ionization and excitation equilibrium

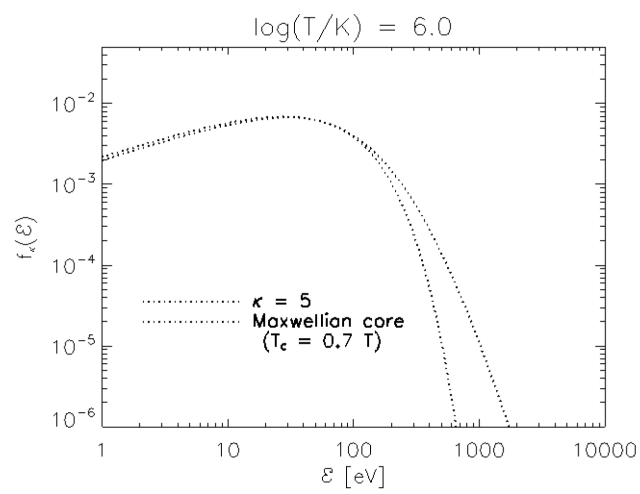
Non-thermal electron κ-distribution

$$f_\kappa(E) = A_\kappa \frac{2E^{1/2}}{\pi^{1/2}(kT)^{3/2}}\left(1+\frac{E}{(\kappa-1.5)kT}\right)^{-(\kappa+1)}$$

$$A_\kappa = \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-0.5)(\kappa-1.5)^{3/2}}$$



$$\langle E \rangle = 3kT/2 \qquad p = NkT$$



$$E \to \infty,\quad f(E) \approx const. \times E^{-(\kappa+1)}$$

Line intensities

level population

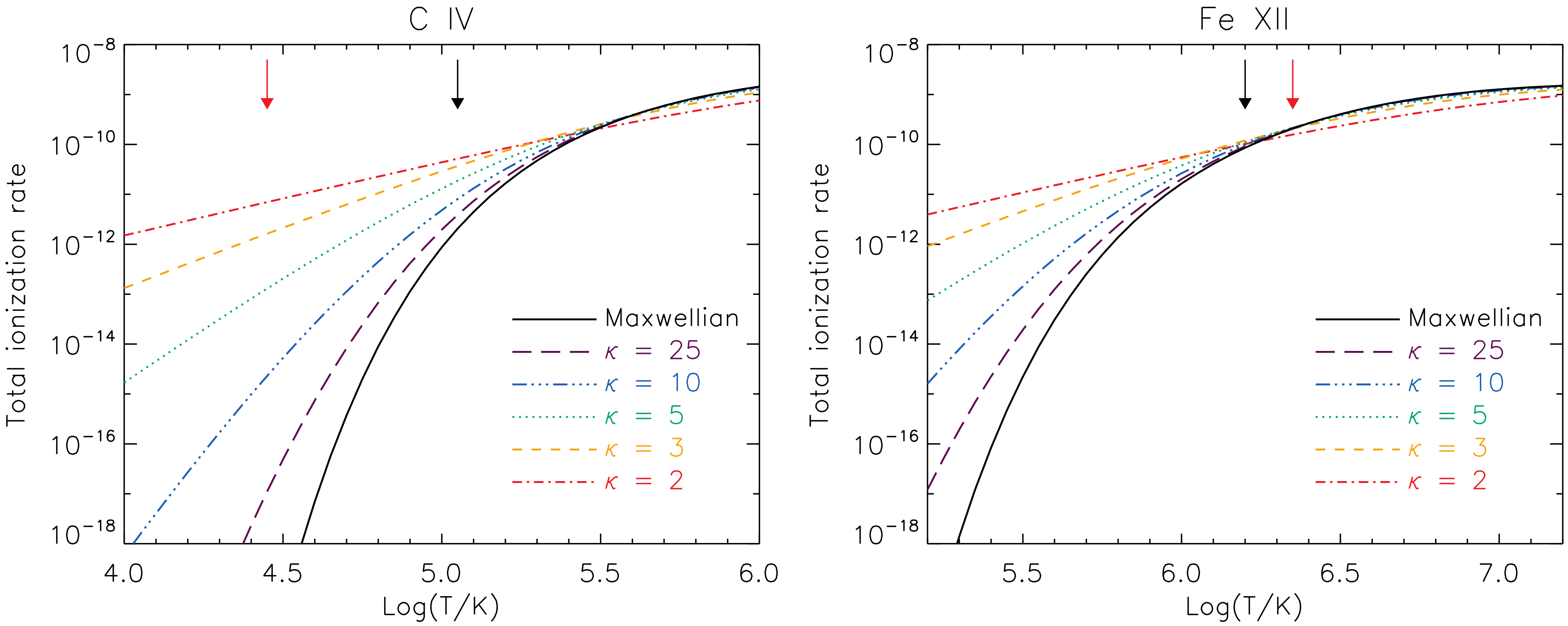
ion abundance

$$I_{ij} = \frac{hc}{4\pi\lambda_{ij}} A_{ij} \int \frac{1}{N_e} \frac{N_{E,i}^{+k}}{N_E^{+k}} \frac{N_E^{+k}}{N_E} \frac{N_E}{N_H} \frac{N_H}{N_e} N_e^2 \, dl$$

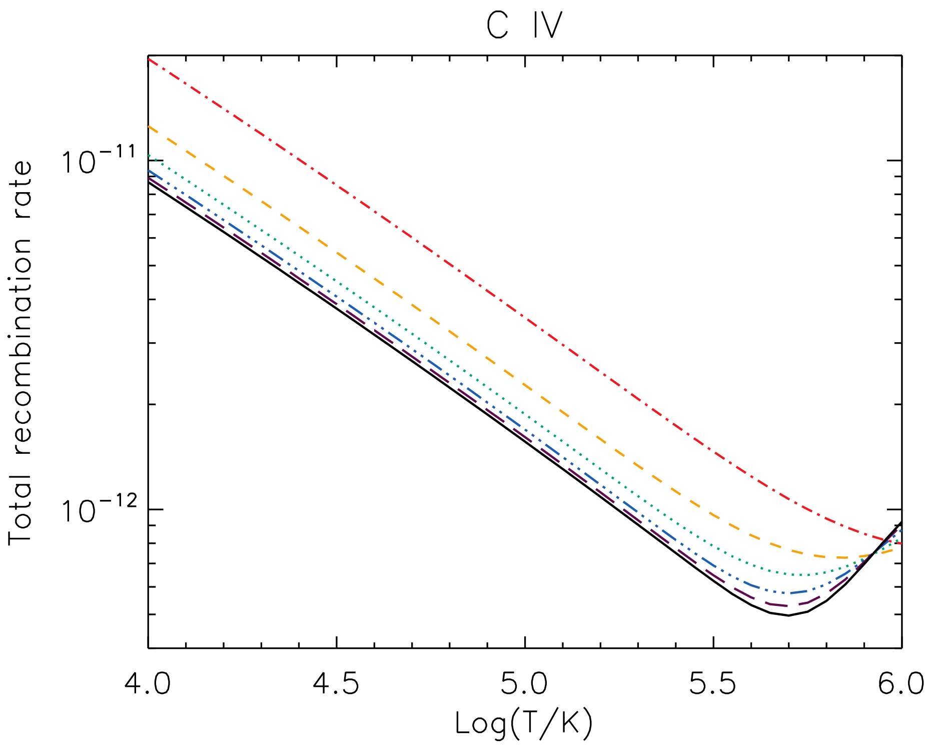
Ionization equilibrium for the k-distributions

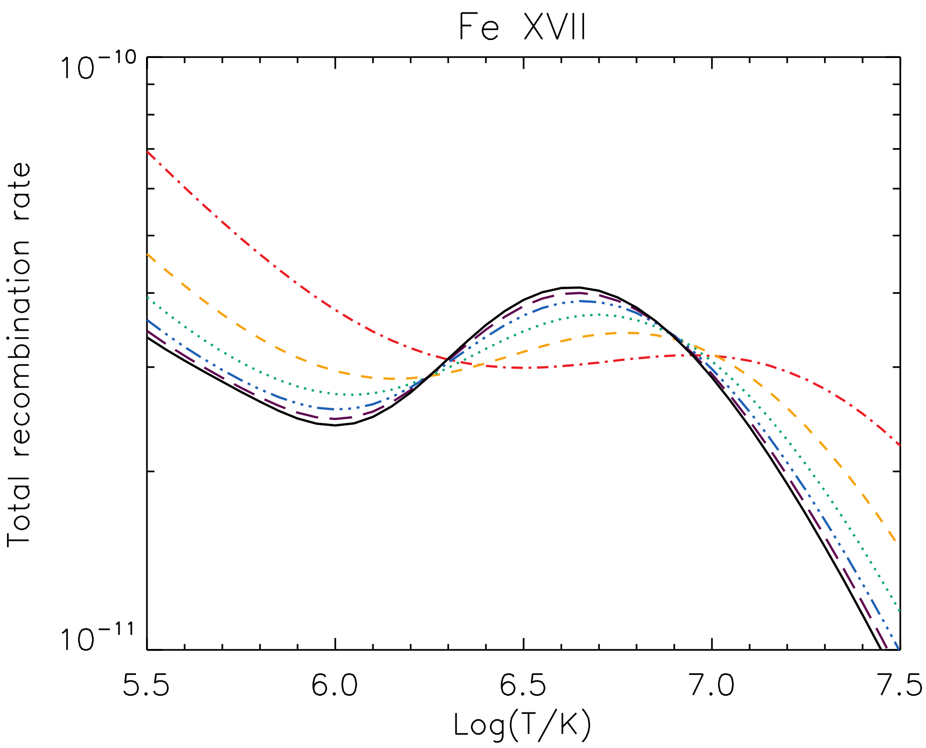
- older calculations for the κ-distributions (Dzifčáková, 1992&2002, Wannawichian *et al.*, 2003) correspond to atomic data by Mazzotta *et al*., 1998 and involve 12 elements only
- new calculation of the ionization equilibrium for the Maxwellian distribution (Dere, 2007)
- the latest calculations for the κ-distributions (Dzifčáková & Dudik, 2013) involve the elements with Z ≤ 30.

Ionization rates

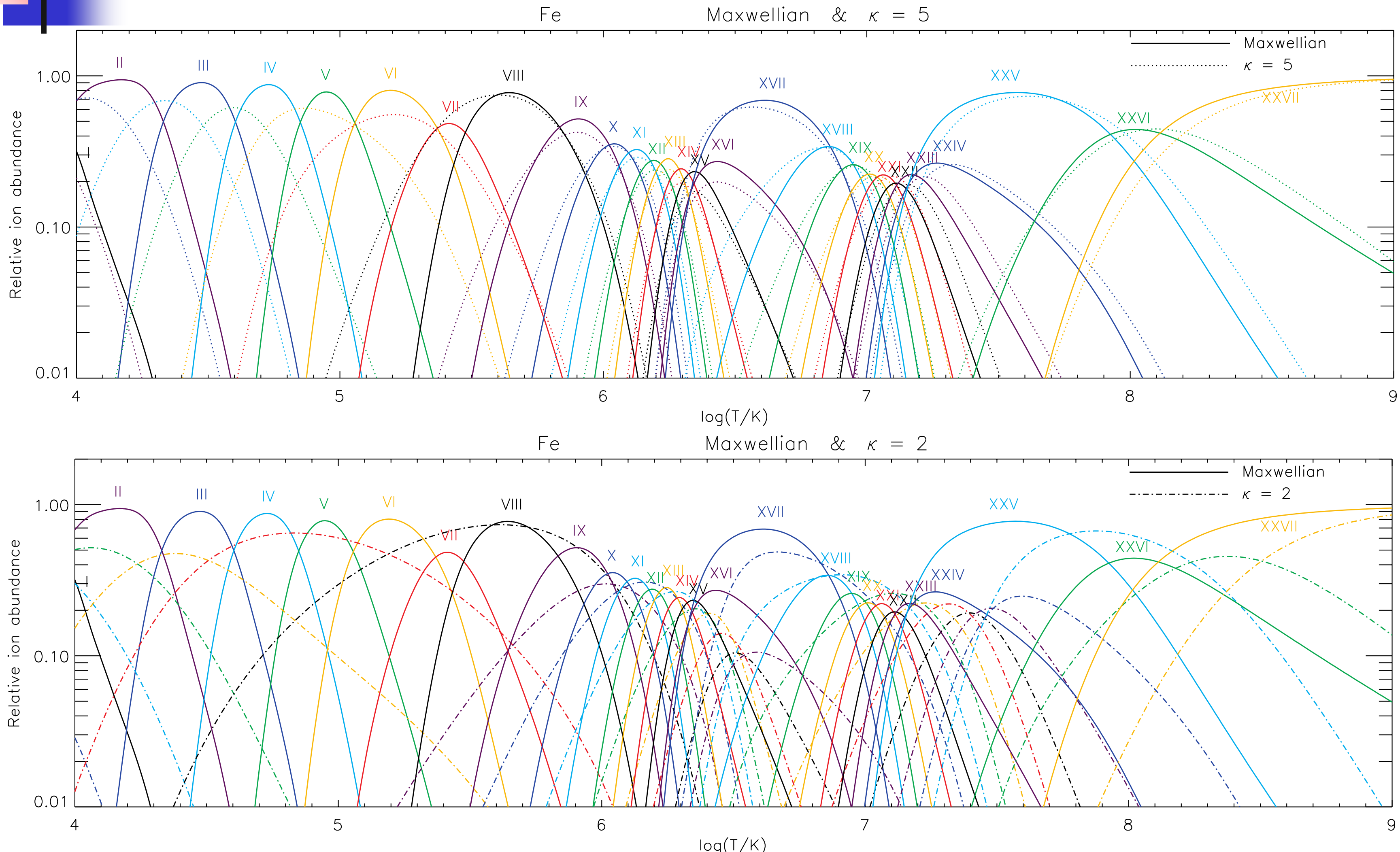


Recombination rates

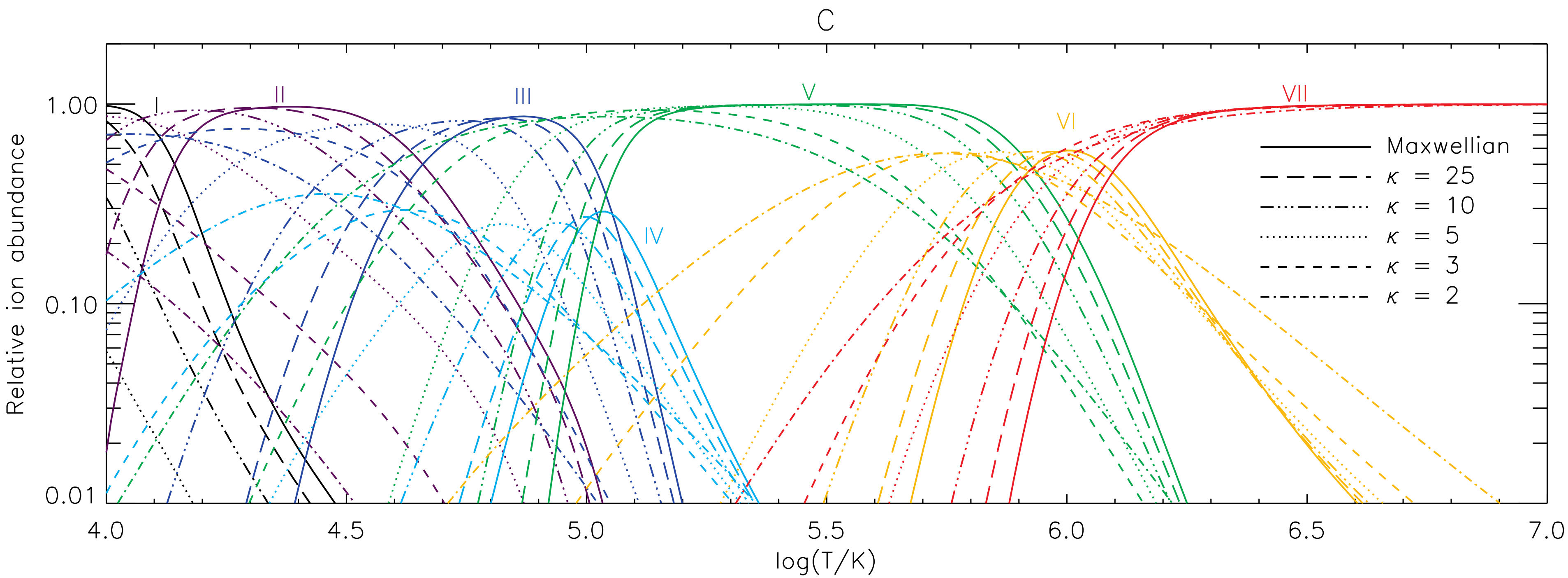




Ionization equilibrium



Ionization equilibrium



Excitation Equilibrium for the k-distributions

Intensity: $$I_{ij} = \frac{hc}{4\pi\lambda_{ij}} A_{ji} \int \frac{1}{N_e} \frac{N_{E,j}^{+k}}{N_E^{+k}} \frac{N_E^{+k}}{N_E} \frac{N_E}{N_H} \frac{N_H}{N_e} N_e^2 \, dl$$

Coronal conditions:

Excitation: collisional e$^-$, p, radiation field

De-excitation: radiative, collisional e$^-$, p

Collisional rates: cross sections σ / collisional strengths Ω

$$\langle \sigma_{ji} \mathrm{v} \rangle = \int \sigma \mathrm{v} f(\mathrm{v}) \, d\mathrm{v} = \frac{const.}{(kT)^{1/2}} \frac{Y_{ji}}{\omega_j},$$

$$\Omega_{ji} = \frac{\omega_j}{\pi a_0^2} \frac{E_j}{I_H} \sigma_{ji}$$

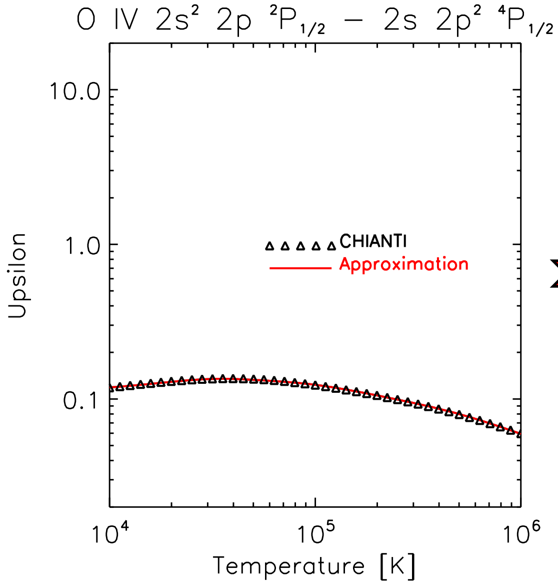
Atomic data

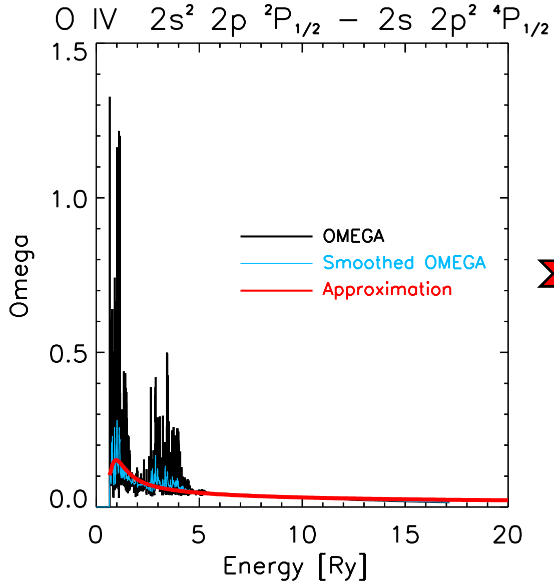
- Requirements – a large amount of data ⟶ CHIANTI
- CHIANTI contains atomic data for the majority of the astronomical interesting ions and has a very good software support.
- CHIANTI allows quick computation and analysis of solar spectra and it is an important diagnostic tool of physical parameters of the solar plasma.
- **PROBLEM:** CHIANTI database (also the other databases) contains only the collision strengths averaged through the Maxwellian distribution.

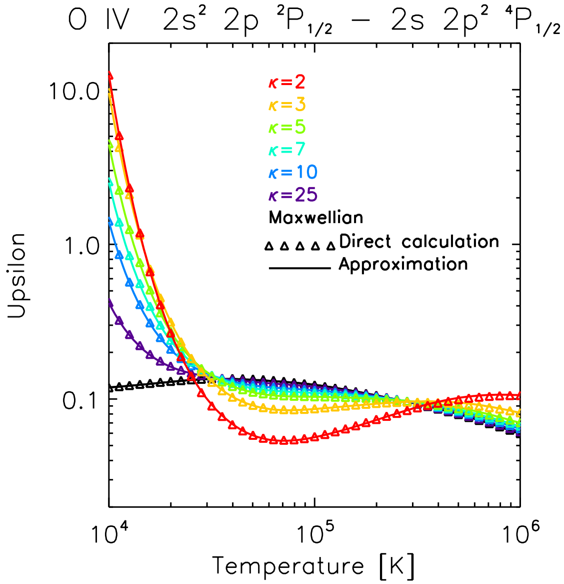
Calculation

$$\Omega = \sum_{k=0}^{k_{\max}} C_k u^{-k} + D\ln(u), \qquad u = E_i/E_{ij} \qquad \Upsilon = C_0 + \left(\sum_{k=1}^{k_{\max}} y C_k \mathbf{E}_k(y) + D\mathbf{E}_1 \right) e^y,$$

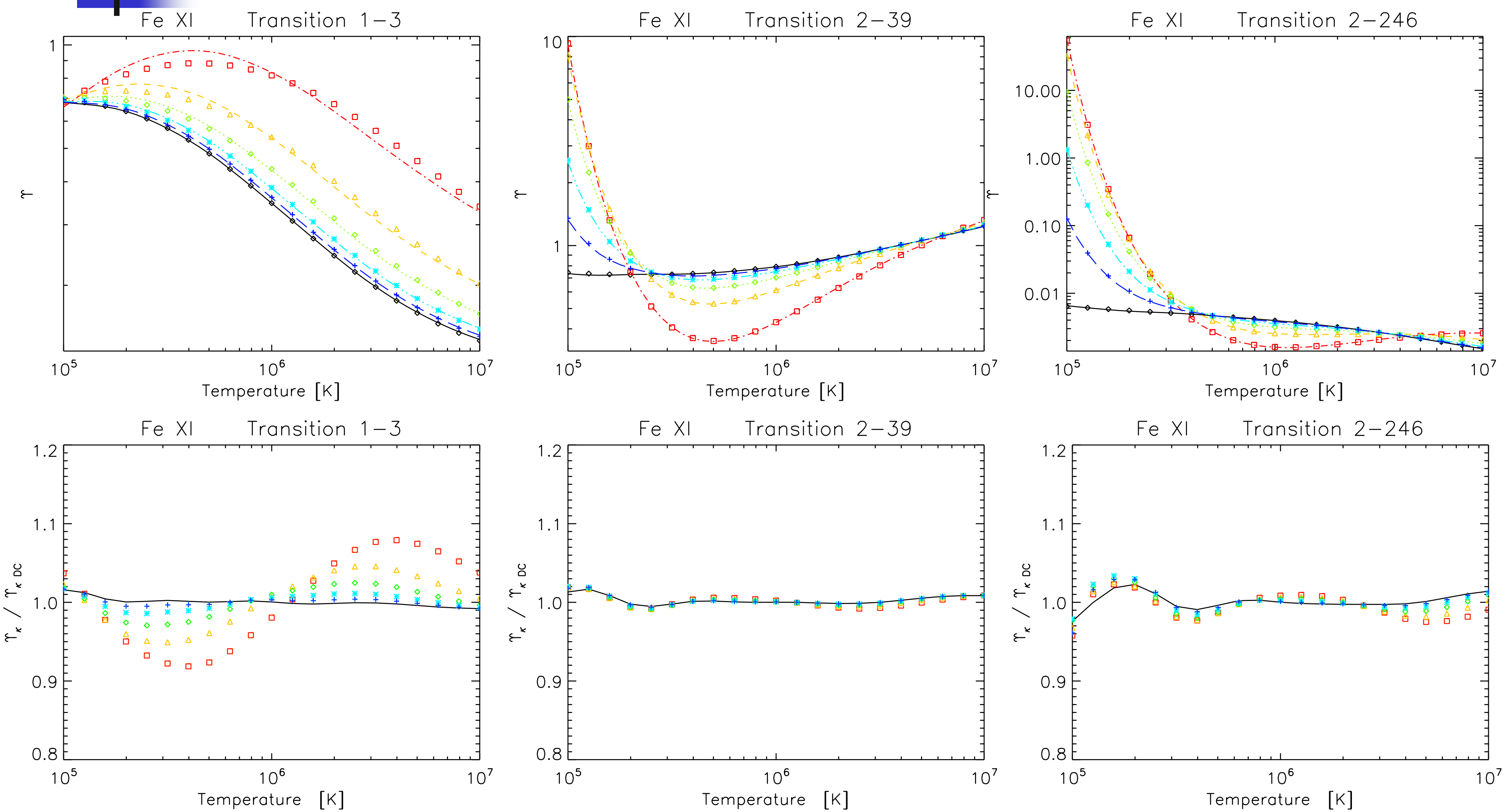
1. Approximation of $\Upsilon_{\mathrm{Maxwell}}$ ➔ 2. Calculation of Ω ➔ 3. Calculation of $\Upsilon_{\mathrm{non\_th}}$



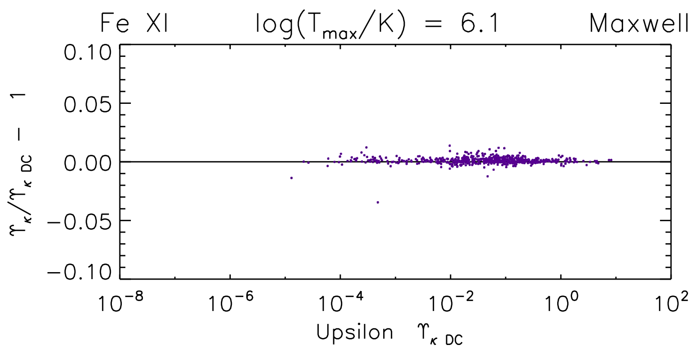


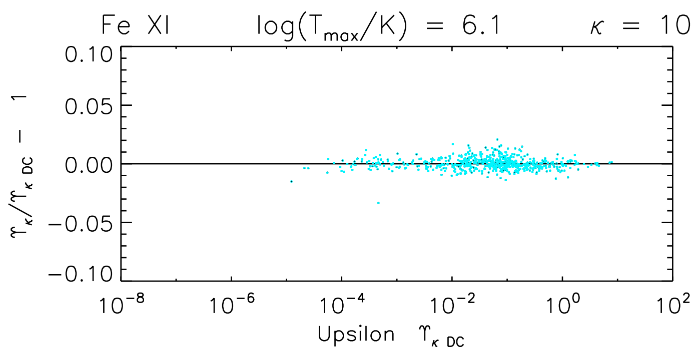


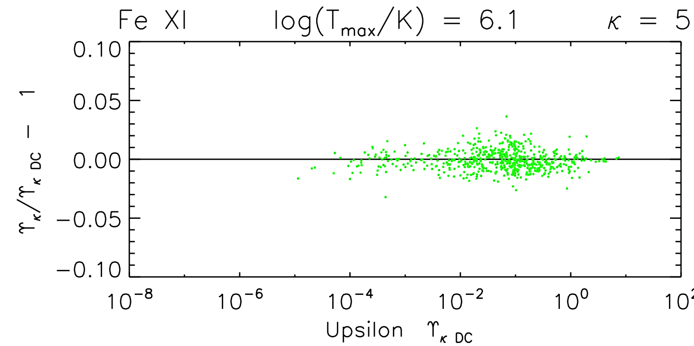
Comparison
Fe XI

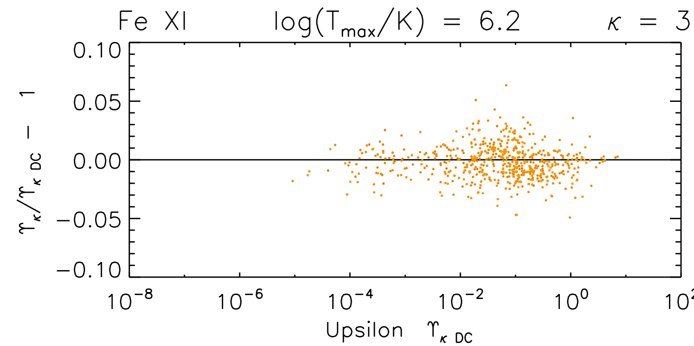


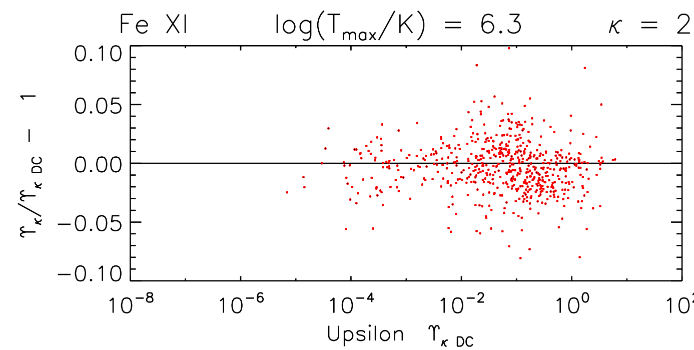
Comparison
Fe XI





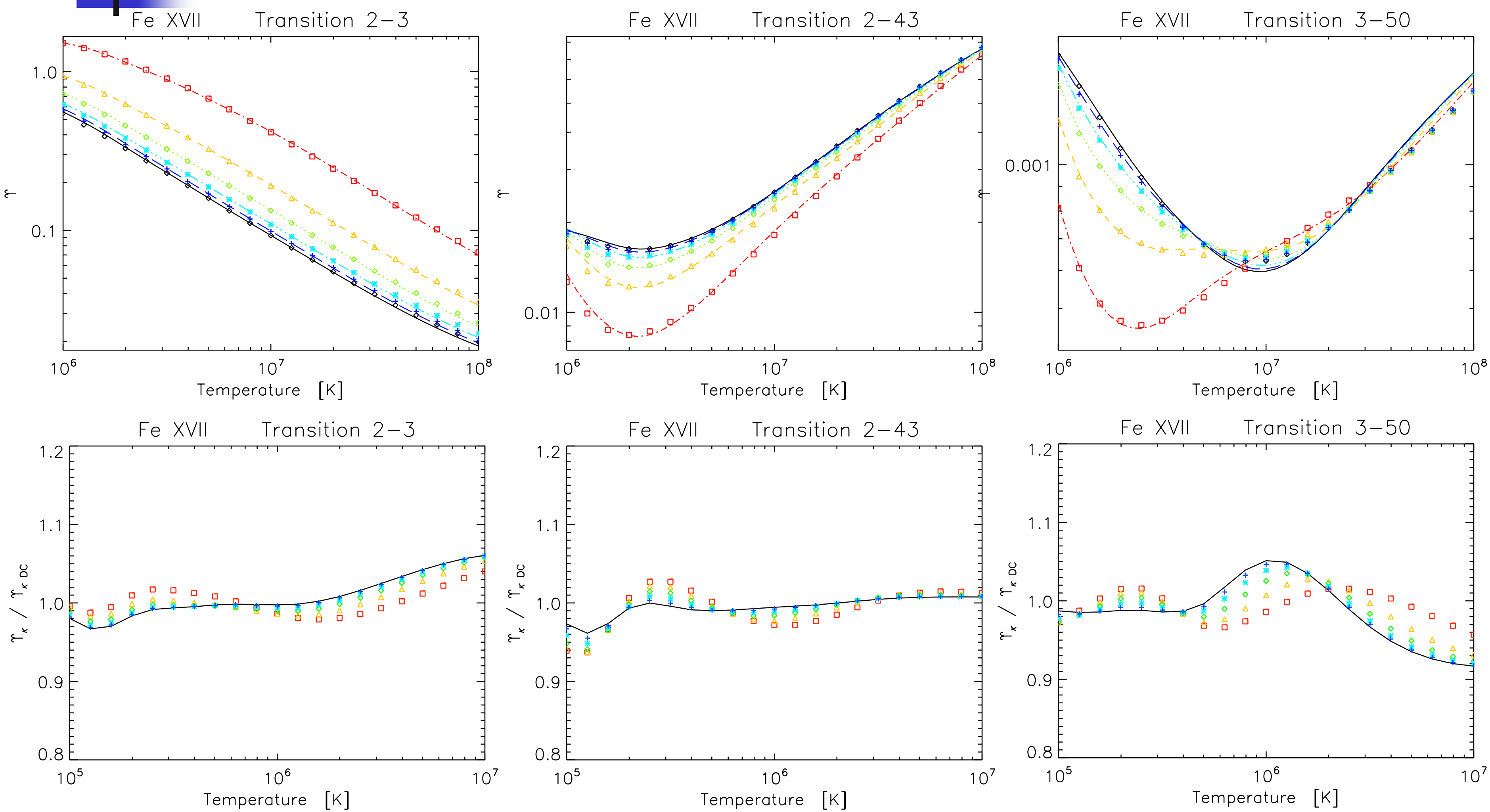




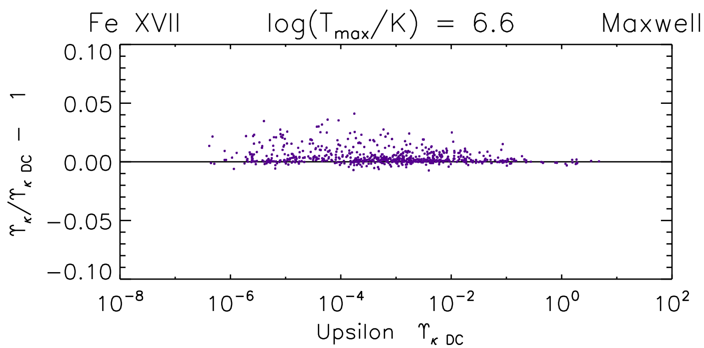


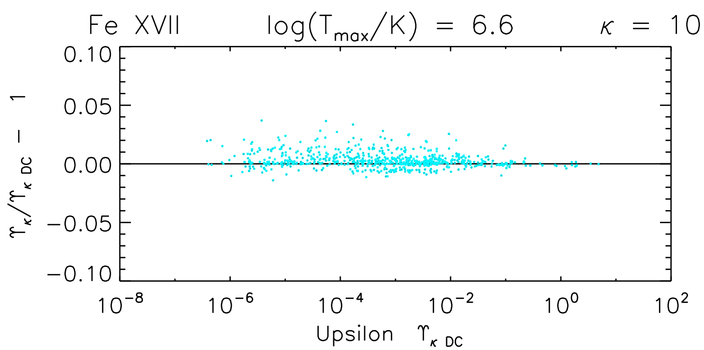
Many thanks to CHIANTI team for data!

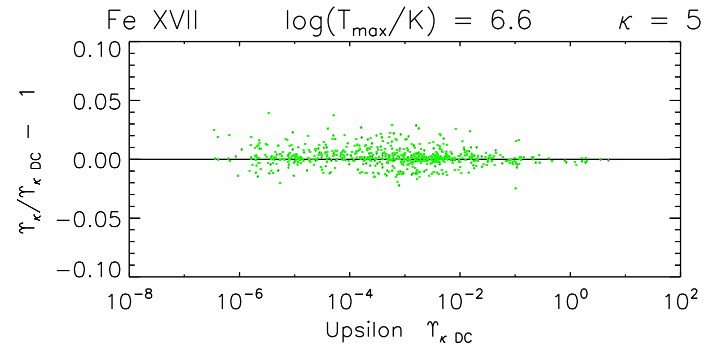
Comparison
Fe XVII

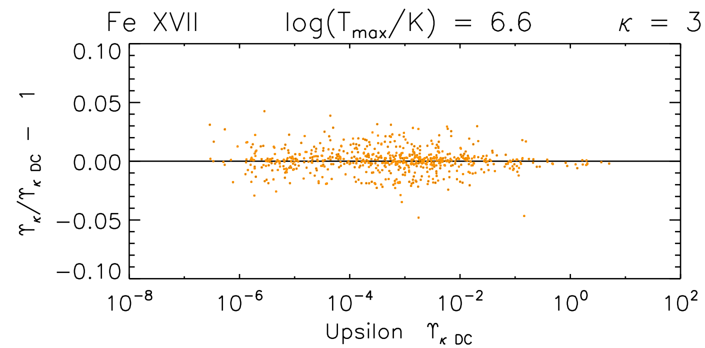


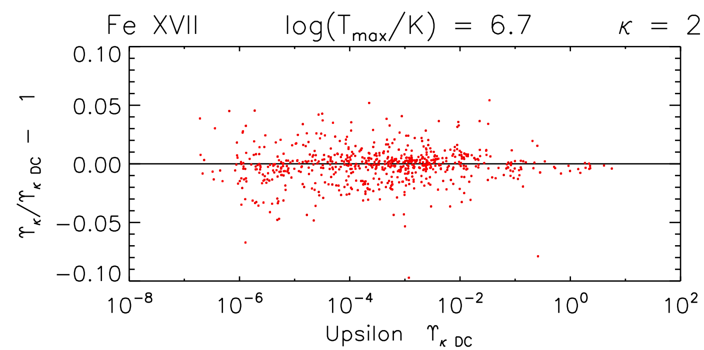
Comparison
Fe XVII









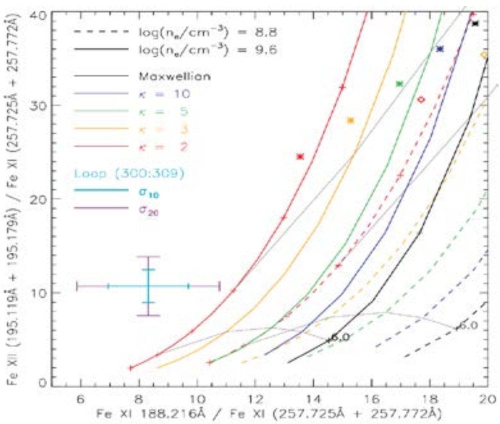


KAPPA package

- KAPPA package - software and newly updated extended database (corresponds to CHIANTI version 7.1) allows us to calculate the line synthetic spectra and continua for the κ-distributions with $\kappa = 2, 3, 4, 5, 7, 10, 15, 25$ and 33
- database corresponds to the CHIANTI 7.1
- KAPPA package uses many original CHIANTI routines and it is impossible to run KAPPA package without CHIANTI
- subdirectories within the kappa database contain data files with the ionization equilibria for the κ-distributions in CHIANTI format, ionization and recombination rates, pre-calculated electron excitation and de-excitation rates, and data for the calculation of continua
- within few weeks we plan to put a freely available version of KAPPA package on the webpage of our institute

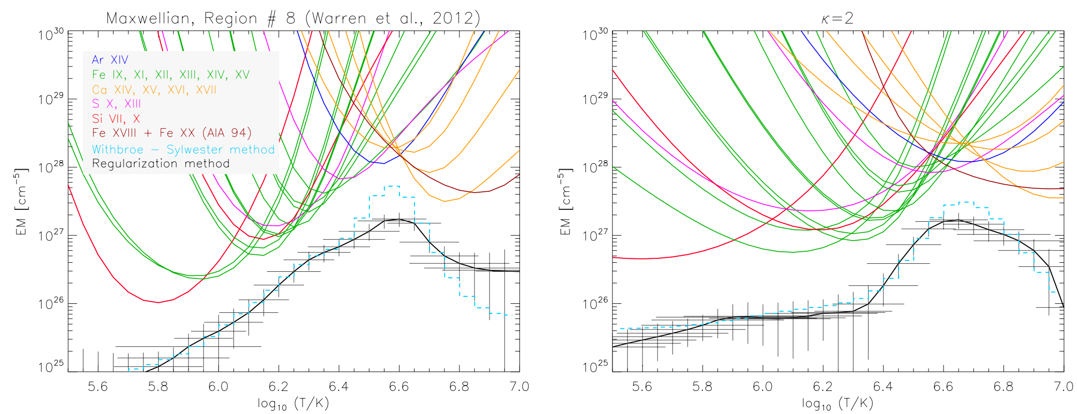
What is possible to investigate?

Diagnostics



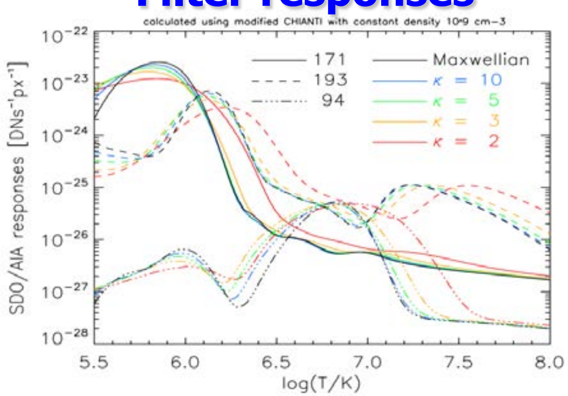
see poster P42

DEM



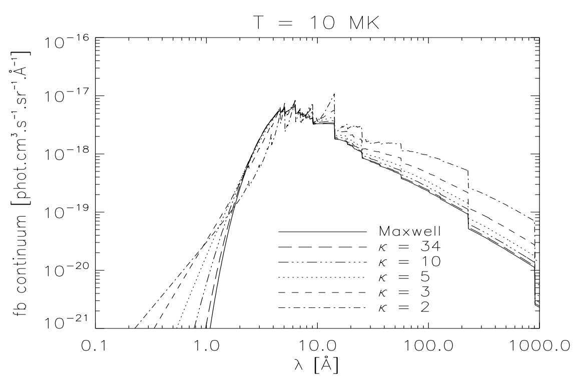
Mackovjak, Dzifcakova, Dudik, 2014

Filter responses



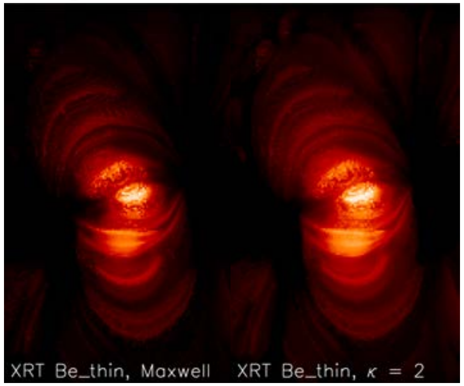
Dudik, et al., 2009

Continuum



Dudik, et al., 2012

Synthetic emission



Dzifcakova, et al., 2012

Summary

The κ–distributions

- influence the ionization and excitation equilibria, and the line intensities
- change the shape of continua
- affect diagnostics of temperature, mainly in the transition region
- can model a plasma affected by the electron beam
- ....

Now we have the useful tool, KAPPA package, that can help in the analysis of astrophysical plasmas out of thermal equilibrium characterized by an enhanced power-law tail of particles.


Thank you very much
for your attention

Minimalisation of possible errors

The fulfilment of the conditions for coefficients guarantees the correct behaviour of Ω for high and threshold energies. The simplest expressions for Ω correspond to expressions which have been often used e.g. by Mewe (1972).

It is difficult to compare data for all transitions. Possible errors in the approximation of Ω cannot be excluded. Their influence on the computation of $\Upsilon_{non\text{-}th}$ have been minimised by using:

$$\Upsilon_{non-th} = \Upsilon^{CHIANTI}_{Maxwell} \frac{\Upsilon^{approx}_{non-th}}{\Upsilon^{approx}_{Maxwell}}.$$